

## An overview of the crop model STICS

N. Brisson<sup>a,\*</sup>, C. Gary<sup>a</sup>, E. Justes<sup>a</sup>, R. Roche<sup>a</sup>, B. Mary<sup>a</sup>, D. Ripoche<sup>a</sup>,  
D. Zimmer<sup>b</sup>, J. Sierra<sup>a</sup>, P. Bertuzzi<sup>a</sup>, P. Burger<sup>a</sup>, F. Bussi re<sup>a</sup>,  
Y.M. Cabidoche<sup>a</sup>, P. Cellier<sup>a</sup>, P. Debaeke<sup>a</sup>, J.P. Gaudill re<sup>a</sup>, C. H nault<sup>a</sup>,  
F. Maraux<sup>c</sup>, B. Seguin<sup>a</sup>, H. Sinoquet<sup>a</sup>

<sup>a</sup> *D partement environnement et agronomie INRA, Avignon, cedex 9, France*

<sup>b</sup> *Division drainage CEMAGREF, Antony, France*

<sup>c</sup> *CIRAD, Montpellier, France*

### Abstract

STICS is a model that has been developed at INRA (France) since 1996. It simulates crop growth as well as soil water and nitrogen balances driven by daily climatic data. It calculates both agricultural variables (yield, input consumption) and environmental variables (water and nitrogen losses). From a conceptual point of view, STICS relies essentially on well-known relationships or on simplifications of existing models. One of the key elements of STICS is its adaptability to various crops. This is achieved by the use of generic parameters relevant for most crops and on options in the model formalisations concerning both physiology and management, that have to be chosen for each crop. All the users of the model form a group that participates in making the model and the software evolve, because STICS is not a fixed model but rather an interactive modelling platform. This article presents version 5.0 by giving details on the model formalisations concerning shoot ecophysiology, soil functioning in interaction with roots, and relationships between crop management and the soil–crop system. The data required to run the model relate to climate, soil (water and nitrogen initial profiles and permanent soil features) and crop management. The species and varietal parameters are provided by the specialists of each species. The data required to validate the model relate to the agronomic or environmental outputs at the end of the cropping season. Some examples of validation and application are given, demonstrating the generality of the STICS model and its ability to adapt to a wide range of agro-environmental issues. Finally, the conceptual limits of the model are discussed.

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### 1. Introduction of the history and aims of the system

The aims of STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) correspond to those of a large number of existing models (Whisler et al., 1986). It is a daily time-step crop

\* Corresponding author. Present address: Climat, Sol et Environnement, INRA, Agroparc, domaine St Paul, 84140 Avignon Cedex 9, France. Tel.: +33-4-32-72-23-83; fax: +33-4-32-72-23-62

E-mail address: [brisson@avignon.inra.fr](mailto:brisson@avignon.inra.fr) (N. Brisson).

model with input variables relating to climate, soil and the crop system. Its output variables relate to yield in terms of quantity and quality and to the environment in terms of drainage and nitrate leaching. The simulated object is the crop situation for which a physical medium and a crop management schedule can be determined. The main simulated processes are crop growth and development as well as the water and nitrogen balances.

STICS has been developed since 1996 at INRA (France) in collaboration with other research (CIRAD<sup>1</sup>, CEMAGREF<sup>2</sup>) or professional (ITCF<sup>3</sup>, CETIOM<sup>4</sup>, AGPM<sup>5</sup>, etc.) institutes. Despite the renown and availability of existing models (CERES: Ritchie and Otter, 1984; ARC-WHEAT: Weir et al., 1984; EPIC: Williams et al., 1989; SUCROS: van Keulen and Seligman, 1987, etc.), new models appear regularly in the literature (Amir and Sinclair, 1991; Brisson et al., 1992a; Hunt and Pararajasingham, 1995; Kanneganti and Fick, 1991; Maas, 1993; McMaster et al., 1991; Teittinen et al., 1994). As Sinclair and Seligman (1996) explained, this is due to the fact that no one universal model can exist in the field of agricultural science and that it is necessary to adapt system definition, simulated processes and model formalisations to specific environments or to new problems (technical, genetic, environmental, etc.). These same authors insist on the heuristic potential of modelling, a determining element in the development of STICS.

From a conceptual point of view, STICS is made up of a number of original parts relative to other crop models (e.g. simulation of crop temperature, simulation of many techniques) but most of the remaining parts are based on conventional formalisations or have been taken from existing models. Its strong points are the following:

- its ‘crop’ generality: adaptability to various crops (wheat, maize, soybean, sorghum, flax, grassland, tomato, beetroot, sunflower, pea, rapeseed, banana, sugarcane, carrot, lettuce, etc.).
- its robustness: ability to simulate various soil–climate conditions without considerable bias in the outputs (Brisson et al., 2002). This feature can jeopardise accuracy at a local scale.
- its ‘conceptual’ modularity: possibility of adding new modules or complementing the system description (e.g.: ammonia volatilisation, symbiotic nitrogen fixation, plant mulch, stony soils, many organic residues, etc.). The purpose of such modularity is to facilitate subsequent developments.
- the external communication created by the model among the users and developers, which drives the model advancement.

This article presents the basics of version 5.0 of the STICS model. A previous paper (Brisson et al., 1998a) was devoted to the detailed description of version 3.0, and concentrated on wheat and maize crops. Many new modules were added to versions 4.0 and 5.0, that will be described in the present paper. Yet details with respect to the equations will not be given knowing that they are available in other documents (published documents or model documentation) that will be properly cited in the following sections.

## 2. Overall description of the system with its components

### 2.1. The system

STICS simulates the behaviour of the soil–crop system over one crop cycle or several crop cycles to simulate rotations. The upper boundary of the system is the atmosphere characterised by standard climatic variables (radiation, minimum and maximum temperatures, rainfall, reference evapotranspiration and possibly wind and humidity) and the lower boundary corresponds to the soil/subsoil interface.

<sup>1</sup> Centre de coopération internationale en recherche agronomique pour le développement.

<sup>2</sup> Centre du Machinisme Agricole, du Génie Rural et des Eaux et Forêt.

<sup>3</sup> Institut Technique des Céréales et Fourrages.

<sup>4</sup> Centre Technique Interprofessionnel des Oléagineux Métropolitains.

<sup>5</sup> Association Générale des Producteurs de Maïs.

Crops are generally perceived in terms of their aboveground biomass and nitrogen content, leaf area index, and the number and biomass (and nitrogen content) of harvested organs. Vegetative organs (leaves, branches or tillers) are thereby not separated in terms of their biomass. Soil is described as a sequence of horizontal layers, each of which is characterised in terms of its water content, mineral nitrogen content and organic nitrogen content. Soil and crop interact via the roots, and these roots are defined with respect to root density distribution in the soil profile.

## 2.2. Simulated processes

Crop growth is driven by the plant carbon accumulation (de Wit, 1978): solar radiation intercepted by the foliage and then transformed into aboveground biomass that is directed to the harvested organs during the final phase of the crop cycle. The crop nitrogen content depends on the carbon accumulation and on the nitrogen availability in the soil. According to the plant type, crop development is driven either by a thermal index (degree-days), a photothermal index or a photothermal index taking into account vernalisation. The development module is used to (i) make the leaf area index evolve and (ii) define the harvested organ filling phase. Water stress and nitrogen stress, if any, reduce leaf growth and biomass accumulation, based on stress indices that are calculated in water and nitrogen balance modules.

Particular emphasis is placed on the effect of crop management on the dynamics of the soil–crop–climate system, knowing that crop specificity relates on crop management and to ecophysiology (e.g. accounting for the various modalities of forage cuttings, fertiliser composition, plastic or crop residue mulching, ...).

## 2.3. Modularity

The STICS model is organised into modules (Fig. 1), with each module composed of sub-modules dealing with specific mechanisms. A first set of three modules deals with the ecophysiology of aboveground plant parts (phenology, shoot

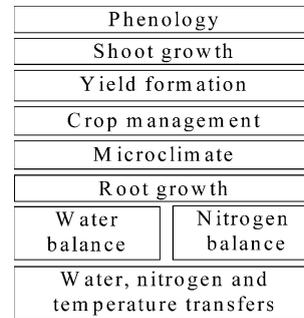


Fig. 1. The various modules of the STICS model.

growth, yield formation), a second set of four modules deals with how the soil functions in interaction with underground plant parts (root growth, water balance, nitrogen balance, soil transfers). The crop management module deals with the interactions between the applied techniques and the soil–crop system. The microclimate module simulates the combined effects of climate and water balance on the temperature and air humidity within the canopy.

## 2.4. The options

Within each module, there are options that can be used to extend the scope with which STICS can be applied to various crop systems. These options relate to ecophysiology and to crop management, for example:

- competition for assimilate between vegetative organs and reserve organs (hereafter referred to as trophic competition);
- considering the geometry of the canopy when simulating radiation interception;
- water circulation in soil macropores;
- the description of the root density profile;
- using a resistive approach to estimate the evaporative demand by plants;
- the mowing of forage crops;
- plant or plastic mulching under vegetation

Certain options depend on data availability. For example, the use of a resistive model is based on availability of additional forcing variables: wind and humidity.

### 3. Detailed description of the modules

#### 3.1. Phenology

##### 3.1.1. The stages

The phenological stages (Table 1) are used as steps for simulating vegetative dynamics (leaf area index and roots) and harvested organ filling (grain, fruit, tuber). The two phenological scales are independent of each other: for example, the onset of filling of the harvested organ (DRP) can occur before or after the ‘maximal leaf area index’ stage (LAX). As in most crop models, the phenological stages simulated by STICS can differ from the stages typically defined in agronomic scales. They are growth stages rather than stages of organ genesis (Brisson and Delécolle, 1991), corresponding to changes in the trophic or morphological strategy of the crop.

For sown crops, emergence is separated into a seed germination phase and a coleoptile–hypocotyl elongation phase. The duration of these phases depends on the temperature in the seedbed, its water status and the sowing depth. Germination failure, as well as the death of seedlings between germination and emergence, are not taken into account (except in the case of freezing). Conse-

quently, plant density introduced as an input parameter corresponds to the density of emerged plants. For planted crops, a latent period between planting and the onset of crop development can be simulated in analogy with the germination phase. In such cases, the leaf area index of the seedling is used to initiate leaf area index dynamics. The occurrence of frost at the seedling stage reduces plant density.

##### 3.1.2. The scale: calculation of development units

The periods separating the successive stages between emergence and physiological maturity are specific to each species and variety. They are expressed in development units, reproducing the plant phenological time: sum of degree-days, possibly multiplied by a photoperiodic or a vernalisation limiting factor, in a similar way to other models (Weir et al., 1984). The photoperiodic factor is calculated between two threshold photoperiods, according to an increasing function for long-day plants and a decreasing function for short-day plants. The vernalisation factor is the ratio between the sum of vernalising days (defined with respect to the thermal optimum for vernalisation) since planting (or since beginning of the dormancy period) and plant vernalisation requirements. Fig. 2 illustrates the dynamics of the accumulation of these development units for wheat and maize, as well as the cumulative effects of photoperiod and vernalisation. After physiological maturity, there may be for certain species a period of dehydration of the harvested organs, which is simulated on the basis of crop temperature.

The sum of degree-days can be calculated on the basis of air temperature or crop temperature (resulting from the calculation of the energy balance, see below). When phenology is calculated on the basis of crop temperature, the duration of phases must be corrected with respect to the standard values expressed in ‘air temperature’ development units (Brisson et al., 2002). The use of crop temperature for crops subjected to water stress makes it possible to simulate accelerated phenology, as suggested by Idso et al. (1978). There are plants for which early plant stress has a reverse effect, i.e. delaying flowering (e.g. rice:

Table 1  
List of the phenological stages of STICS

Vegetative stages	Filling stages
<i>PLT</i> : sowing or planting	
GER <sup>a</sup> then LEV <sup>a</sup> : germination then emergence	
<i>AMF</i> : end of juvenile phase	LAT <sup>b</sup> : beginning of the phase critical for grain number
<i>LAX</i> : maximal leaf area index	<i>DRP</i> : beginning of fruit filling
SEN: beginning of net senescence <sup>c</sup>	NOU <sup>d</sup> : end of fruit setting
LAN: stage when leaf area index is nil <sup>c</sup>	<i>MAT</i> : physiological maturity
<i>REC</i> : harvest	

The stages in italics are compulsory. The others are required as a function of the options chosen.

<sup>a</sup> For sown crops.

<sup>b</sup> For determinate crops.

<sup>c</sup> For the option ‘LAI net’.

<sup>d</sup> For indeterminate crops.

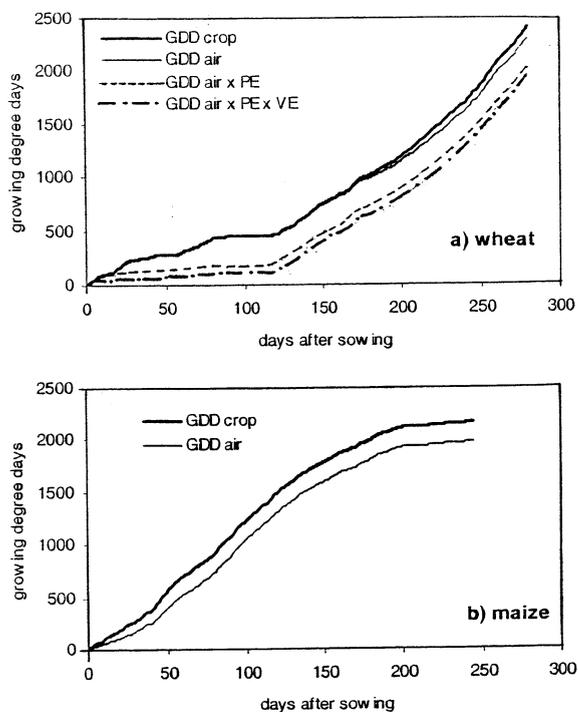


Fig. 2. Dynamics of accumulation of developmental units for (a) wheat and (b) maize, taking into account growing degree-days (GDD) calculated either from air (GDD air) or from crop temperature (GDD crop) and eventually slowed down by photothermal (PE) or vernalization (VE) effects.

Wopereis et al., 1996 or banana: Brisson et al., 1998b). It seems that we lack information about this opposite effect to correctly simulate it. Consequently, a simple hypothesis was introduced in STICS, just allowing to test how flowering delay is related to stress: until the DRP stage, the development unit can be multiplied by a stress factor accounting for the maximum of water and nitrogen stresses.

### 3.2. Shoot growth

#### 3.2.1. LAI

Because of the key role played by leaf area index in the model, the STICS model includes several options for simulating this variable. The standard option, described in Brisson et al. (1998a), directly simulates the leaf area index, as the net balance between growth and senescence. Only exceptional

senescence, related to heat stress, water stress and nitrogen stress, is calculated in addition.

Leaf area index evolves through various phases: growth, stability (for determinate species) and senescence. A first calculation of net leaf growth rate (in  $\text{m}^2 \text{plant}^{-1} \text{degree-day}^{-1}$ ) is only related to phenological stages; it describes a logistic curve of development units taking on an asymptote that is characteristic for the species with an inflection point at the end of the juvenile phase (AMF). This value is then multiplied by the effective crop temperature, the planting density combined with an inter-plant competition factor that is characteristic for the variety, and the water and nitrogen stress indices (Section 3.2.4). These calculations are illustrated in Fig. 3.

The robustness of the above formalisation was tested for numerous crops including crops whose vegetative phase overlaps the filling phase (e.g. soybean and flax). However, when trophic competition between leaves and fruits is a driving force of crop production and crop behaviour (e.g. tomato), leaf growth simulation should also take assimilate availability into account (e.g. of 'indeterminate'<sup>6</sup> crops such as tomato). This is done through a trophic stress index (Section 3.2.4).

For 'determinate' crops, the leaf area index remains constant between the LAX and the SEN stages. For 'indeterminate' crops, this plateau phase does not exist in structural terms but can occur if the source/sink ratio is sufficiently extreme to halt leaf growth. From the SEN to the LAN stages, the leaf area index decreases as a linear function of the developmental units. Water stress can result in early senescence and early maturity due to the higher crop temperature used to calculate the developmental units.

The concept of lifetime (in degree-days), used for example by Maas (1993), is applied to above-ground biomass production, taking into account the senescence induced by water stress and nitrogen stress. Part of the biomass produced on a given day is therefore lost through senescence once the

<sup>6</sup> In STICS, 'indeterminate' denotes species for which there is trophic competition between vegetative organs and harvested organs.

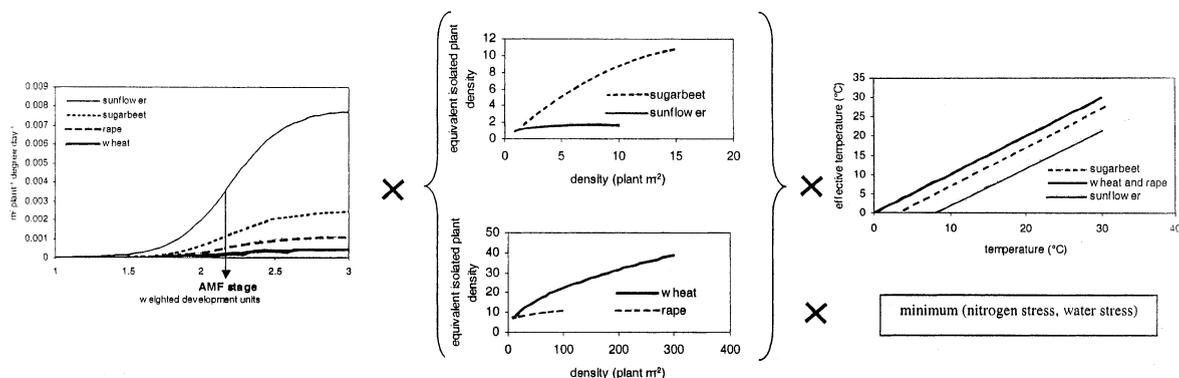


Fig. 3. The steps of the calculation of the LAI growth in STICS as parameterised for 4 various crop (wheat, rape, sunflower and sugarbeet). From left to right: In the first part of the figure the developmental units in the X-axis are weighted by the genetic-dependant duration of the LEV-AMF and AMF-LAX phases, so that for the stage LEV  $t$  is 1, for the stage AMF (the inflexion point of the curves) is 2.2 and LAX is 3. In the second part of the figure the density effects are represented, with orders of magnitude different for the various crops. The third part of figure represents the effects of temperature, nitrogen and water stress.

lifetime has elapsed. This part is estimated at 80%, taking into account the part which was not allocated to leaves when the biomass was established and also the part which was remobilised during its senescence. In the case of severe stress (a threshold of 0.7 was chosen for the minimum of water stress and nitrogen stress indices) or low temperatures (below temperatures that are effective for leaf growth), the loss of biomass due to senescence leads to a reduction in the leaf area index, assuming that the gross growth of new leaves can no longer compensate for senescence. The conversion from senescent biomass to leaf area is made by a specific leaf area parameter.

A more sophisticated option was incorporated into version 5.0 where LAI evolution results from gross growth and senescence as a result of the natural ageing of the foliage and stress-induced senescence. This method for calculating LAI is closer to the usual methods (Milroy and Goyné, 1995; Chapman et al., 1993). Growth is simulated in the same way as in the previous option and the simulation of senescence is based on the notion of lifetime applied directly to LAI. This option has a number of advantages: the LAX stage and SEN stage (Table 1) are of no use and it is possible to simulate the effect of nitrogen over-fertilisation on prolonged foliage activity.

A simpler option was also incorporated that bypasses the LAI calculation to directly calculate a

soil cover rate that makes it possible to simulate short duration-cycle crops, such as lettuce (de Tourdonnet, 1999).

### 3.2.2. Radiation interception

For homogeneous crops, it is advised to use the Beer's law analogy, as a function of LAI, requiring just one parameter. For row crops, a method for calculating radiation interception is proposed which takes crop geometry into account in a simple fashion (Brisson et al., 1999). In this method, the interrow is represented as 20 points equally distributed and the radiation received at each point is calculated from the critical angles below which this point receives solar radiation directly. On either side of these critical angles, radiation is reduced due to absorption by the crop; the radiation received at each point is the sum of radiation intercepted and transmitted by the crop and the non-intercepted radiation. Both of these components include a direct part and a diffuse part, taking row orientation into account and assuming that the direct radiation evolves sinusoidally during the day. The diffuse radiation/total radiation ratio is calculated according to Spitters et al. (1986).

The dynamic estimation of crop geometry is based on the following hypotheses: the crown (or the crop's leaves) occupies a volume whose shape is simple and whose cross-section is rectangular or

triangular (the base of which can either be at the bottom or at the top of the plant), and this volume can be estimated from the LAI, the interrow value, a leaf density value assumed to be constant with respect to the volume and the thickness/width ratio of the shape. It is possible to limit crop height (genetic or technical maximum); then, when the maximal height has been reached, the shape can only change through its width. Certain cropping operations aimed at controlling the shape of the plant or at reducing the LAI (leaf removal) can be simulated.

One way of using the radiation transfer module is to simulate the effect of row orientation, illustrated by Fig. 4. For a homogeneous crop such as maize, this effect is minor, which justifies using the Beer's law analogy. This is not the case for vineyards.

### 3.2.3. Radiation use efficiency

STICS directly calculates the daily accumulation of aboveground biomass, which is the net result of

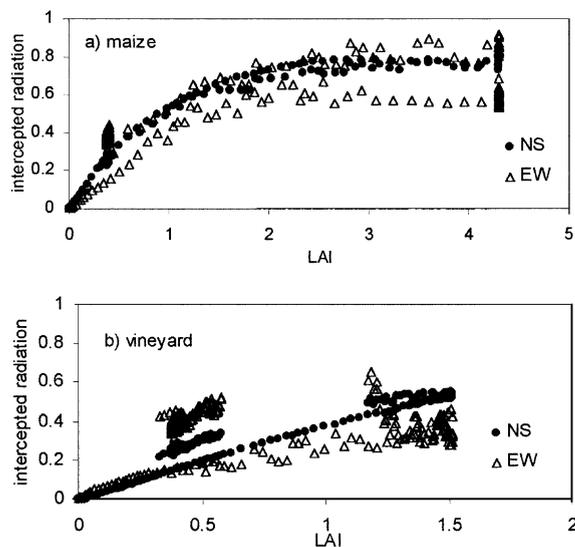


Fig. 4. Proportion of intercepted radiation as a function of LAI for (a) maize and (b) vine simulations taking into account the row orientation (NS = North–South, EW = East–West). The plateau-type simulation of the LAI (the option ‘LAI net’ was used for these simulations) results in vertical thresholds particularly visible in figure (a). In Figure (b), the groups of points with high intercepted radiation for both orientations correspond to cloudy days with all radiation in a diffusive form.

the processes of photosynthesis, respiration and root/shoot partitioning. This daily accumulation is a function of the intercepted radiation according to a parabolic law involving the maximal radiation use efficiency (RUE). Maximal values of RUE, specific to each species and phenology-dependant, are given as input parameters. The maximal RUE is lower during the juvenile phase because it takes into account the preferential accumulation of assimilates in the roots at the beginning of the cycle. For crops accumulating high-respiratory cost components, such as lipids, the maximal RUE needs to be diminished during the filling phase. Those maximal RUE values can be reduced by non-optimal crop temperatures or by water (deficit or excess) and nitrogen stresses, to calculate actual RUE. RUE can also be modified if the atmosphere is CO<sub>2</sub>-enriched (accounting for direct effects of climatic changes) according to a formalisation adapted from Stockle et al. (1992). For perennial plants, there may be a compartment of reserves that is remobilised during spring and that is actively involved in the onset of aboveground growth.

The daily growth rates calculated for various crops can be related to the intercepted radiation to estimate average radiation use efficiencies (Fig. 5). The orders of magnitude obtained for maize and soybean corroborate those found in the literature

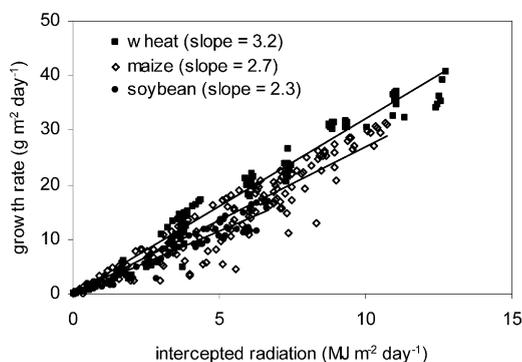


Fig. 5. Estimation of average radiation use efficiencies (slopes of the linear regressions indicated in the  $x$ -axis as  $\text{MJ m}^{-2} \text{ day}^{-1}$ ) from simulated data for wheat, maize and soybean. The simulations correspond to actual case studies for which the model was validated (Brisson et al., 2002). The maize crop was water stressed, while the wheat crop was over-fertilised.

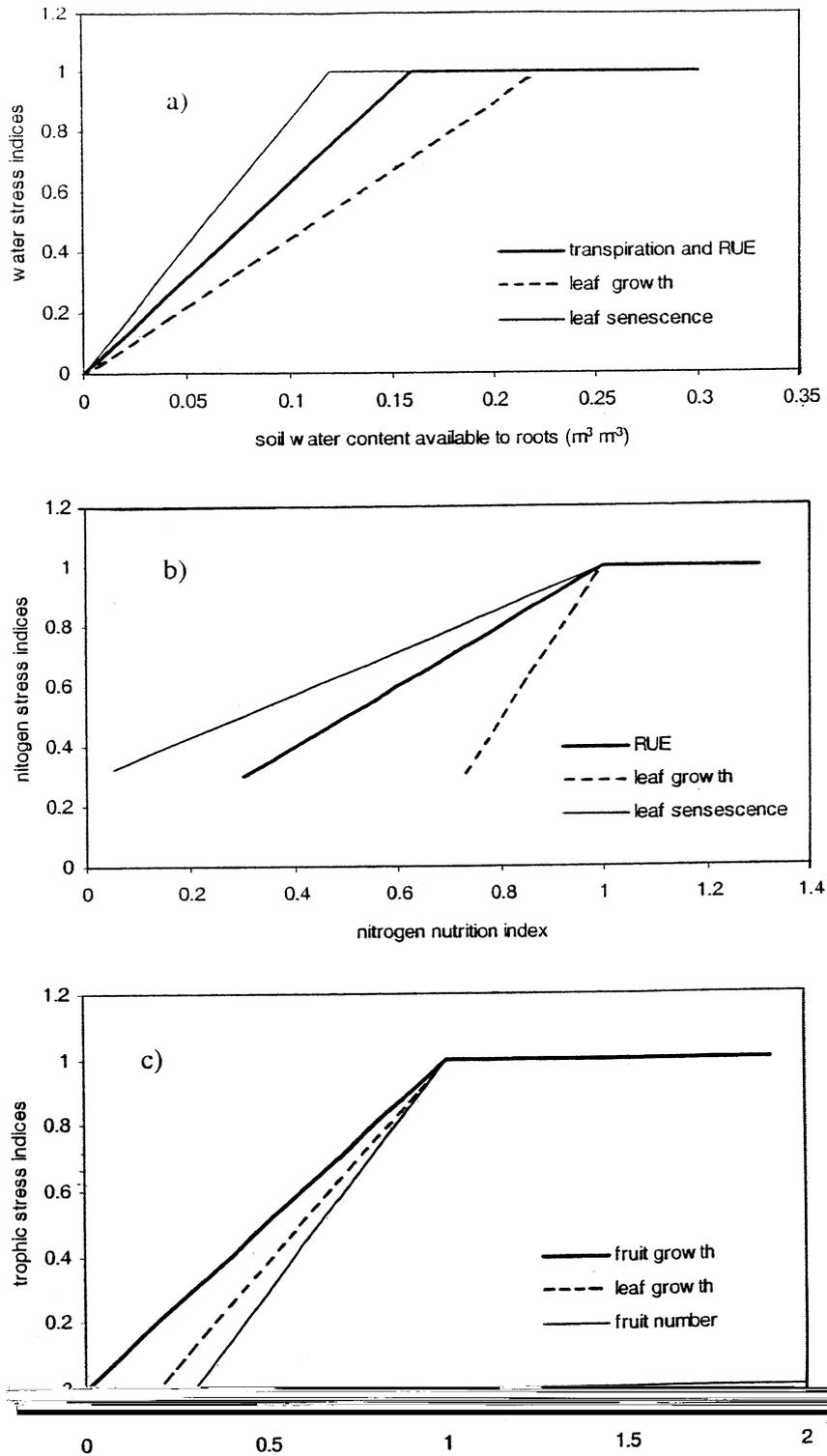


Fig. 6. Calculation of the various stress indices: (a) water stress indices, (b) nitrogen stress indices and (c) trophic stress indices (for indeterminate crops only).

(Gosse et al., 1986). The value for wheat can appear relatively high if it is not specified that the crop was over-fertilised. This highlights the need of accounting for water and nitrogen stress when calculating RUE.

#### 3.2.4. *Stress indices*

The stress indices are values between 0 and 1 that reduce the vital plant functions. These indices mostly result from relationships calculated as functions of stress state variables. The soil water content available to roots is the water stress variable, the nitrogen nutrition index is the nitrogen stress variable and the source/sink ratio is the trophic stress variable. The relationships are simple bilinear functions, i.e. equal to a constant until a critical level of the state variable is reached and then linearly decreasing, using just one crop-dependant parameter (Fig. 6).

Concerning water stress, the calculation of the thresholds for transpiration (RUE) and leaf growth (Section 3.7.3), relies on an analytical formulation derived from more mechanistic models (Brisson, 1998). The stress index for leaf senescence is supposed to be the latest with respect to the onset of the water constraint and the threshold is estimated as half the value for leaf growth.

Concerning nitrogen stress, all indices have a lower limit estimated at 0.3. The index for the RUE is strictly the nitrogen nutrition index while the indices for leaf growth and leaf senescence have been tested as being more and less severe, respectively (gramineae and mustard: Dorsainvil, 2002).

The trophic indices are only active for indeterminate plants and account for the lack of assimilate (or carbon) to allow the potential plant growth. The index for fruit growth is the source/sink ratio. The indices for leaf growth and fruit onset have been tested as being lower (tomato crop: Ortega-Farías et al., 2002), pointing out the priorities in case of assimilate deficit.

The STICS model also includes stresses for frost and anoxia, and thermal stresses affect the RUE and filling of the harvested organs.

### 3.3. *Yield formation*

#### 3.3.1. *Determinate plants*

For determinate species, the number of grains (or other harvested organs) depends on the mean growth rate of the crop during a grain-number determination phase (LAT-DRP). The relationship is linear and introduces the maximal number of grains, a typically genetic parameter. The dry matter and nitrogen accumulated in the grains are calculated by applying linearly increasing ‘harvest indices’ to the shoot biomass and nitrogen. Those model formalisations are inspired from work by Sinclair and collaborators (e.g. Spaeth and Sinclair, 1985). Threshold temperatures for translocation can temporarily halt the filling of harvested organs. The mass of each grain is then calculated as the ratio between yield and the number of grains, although without being able to exceed a genetic limit.

#### 3.3.2. *Indeterminate plants*

For indeterminate plants, the fruits (or other harvested organs) become established between the onset of filling and the end of fruit setting. On each day, during this period, the number of set fruits is the product of a genetic parameter (the potential number of set fruits per plant and per degree-day), the effective temperature and the source-sink ratio (Bertin, 1995). During growth, the fruits pass through compartments corresponding to increasing physiological ages, the number of which is an input parameter. The time fruits spend in a compartment depends on temperature. This simulation technique was inspired from the ‘boxcar-train’ used in the TOMGRO model (Goudriaan, 1986; Jones et al., 1991). In each compartment, fruit growth is equal to the product of a ‘sink strength’ function and the source-sink ratio. The strength of the fruit sink is the derivative of a logistic function that takes the genetic growth potential of a fruit into consideration (Bertin and Gary, 1993).

Several functions representing how indeterminate plants grow depend on the source/sink ratio (Warren-Wilson, 1972). Sources correspond to both the newly formed assimilates and the older remobilisable assimilates (reserves). Reserves re-

present an assimilate compartment which is not located (it can be either in the stems, the leaves or the roots); its size is determined on the basis of the difference between total biomass on the one hand and, on the other hand, the accumulation of biomass in the fruits, green leaves (calculated from the LAI and a specific leaf area), senescent leaves and the structural part of the stems (calculated from a ‘total leaves/structural stem’ ratio assumed to be constant).

The strength of the fruit sink is obtained by adding up, for all the growth compartments, the product of the number of fruits and a growth potential value. The strength of the vegetative sink corresponds to the growth of the leaf area index converted into vegetative biomass. The sensitivity to trophic (or carbon) stress (which is a parameter) is generally higher for fruit number than for leaf and fruit growth (Fig. 6). For tubers (e.g. sugar-beet or potato) or for plants with short fruit setting period, the model does not simulate any competition between number and weight of harvested organs: competition is mainly with leaves.

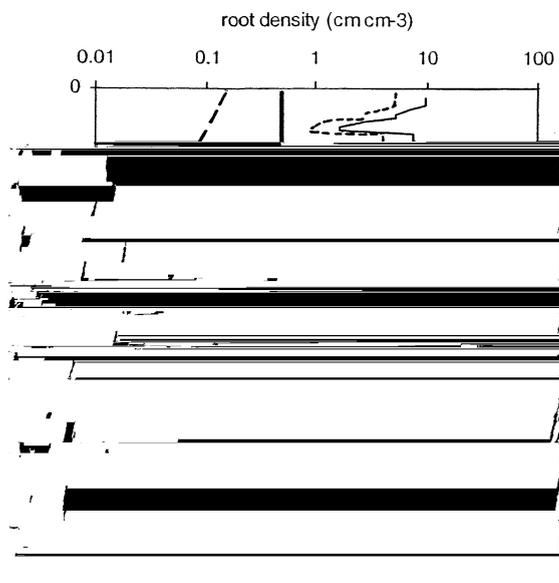


Fig. 7. Comparison of the two options for root density calculation (standard profile—SP and actual density—AD) at two stages of wheat growth (tillering and grain filling). The resulting differences in nitrogen and water uptake are 79 (SP) and 81 (AD) kgN ha<sup>-1</sup> crop cycle<sup>-1</sup> and 270 (SP) and 268 (AD) mm ha<sup>-1</sup> crop cycle<sup>-1</sup>, respectively.

### 3.3.3. Quality

The simulation of the harvested product quality is an original characteristic of the STICS model. The accumulation of various categories of biochemical compounds is simulated simply. Nitrogen is calculated as a function of a ‘nitrogen’ harvest index (harvested organ N/total plant N) that is proportional to the filling phase duration. For sugars and lipids, it is assumed that the concentration is proportional to the dry matter in the organs. Water content is calculated independently, relying on hydration (or dehydration) dynamics based on species parameters and on the evolution of crop temperatures during filling and maturation.

## 3.4. Root growth

### 3.4.1. Root front

In STICS, root growth is separated from above-ground growth: roots act only as water and mineral nitrogen absorbers (under the nitric or ammoniacal form indifferently). A first calculation gives the depth of the root front which advances at a rate that is proportional to the soil temperature with a coefficient that is specific to the species. It depends on the soil water content: slowdown or stop according to how sensitive the species is below the wilting point and at saturation (anoxia). In the case of annual species, the root front begins at the sowing depth; in the case of perennial plants, the initial value of the root front can be deeper in the soil. It stops if it reaches a soil depth that poses an obstacle (physical or chemical) or, finally, when net leaf growth ceases.

### 3.4.2. Root density

A second calculation gives the root density profile according to two possible options. The ‘standard profile’ option makes it possible to calculate the root profile that is effective with respect to absorption, assuming that it always has the same sigmoidal shape established on the basis of plant parameters and of the depth of the dynamic root front (Brisson, 1998). This formalisation assumes that, at the surface, root density always reaches the optimal threshold for water and nitrogen absorption, set at 0.5 cm cm<sup>-3</sup>.

In order to simulate low-density crops, for which root density is never optimal, or in order to take into consideration the effects of constraints imposed by the soil on root distribution, there is a second option that makes it possible to estimate the actual root density profile. Growth in root length is calculated using a logistic function that is analogous to that of leaves and is then distributed in each layer of the soil profile in proportion to the roots present and as a function of the soil constraints (drought, anoxia, penetrability). At the root front, growth in density is constant, knowing that the root front depth is affected by temperature and soil water content (Section 3.4.1). For sown crops, this calculation begins at emergence: between germination and emergence, it is assumed that only the root front grows. For ‘planted’ crops, or perennial crops, the calculation is initiated with an existing root density profile. Each constraint is defined for a given layer in the form of an index between 0 and 1 and assumed to be independent of the others. The resulting index is the product of the elementary indices and determines root distribution in the soil layers. After a lifetime characteristic of the species, the roots senesce and enter the mineralisation process as crop residue at the end of the crop cycle. Root density above  $0.5 \text{ cm cm}^{-3}$  is not taken in account for water and nitrogen absorption.

The differences between the two options in the simulation of the root profiles can be significant (Fig. 7) but the impact on the simulated water and nitrogen uptakes can be not significant because of

the functional root density threshold of  $0.5 \text{ cm cm}^{-3}$ .

### 3.5. Crop management

#### 3.5.1. Water transfer through the canopy

Depending on the irrigation systems used, the supplies can be either over-the-crop, under-the-crop or in the soil (drip irrigation). In the case of under-the-crop irrigation, the water supply is not affected by the mechanisms of rain interception by the foliage. In the case of subsurface drip irrigation, the supply is not subjected to soil evaporation phenomena either.

Water retained on the foliage, directly subjected to the evaporative demand of the surrounding atmosphere, can evaporate, thereby significantly reducing the saturation deficit within the canopy and crop water requirements. Stemflow is estimated first of all in order to avoid overestimating water retention on the foliage. It is a proportion of the incoming rainfall modulated by the leaf area index. The maximum amount of water retained by the foliage is directly proportional to the LAI and varies from one species to another between 0.2 and  $0.7 \text{ mm LAI}^{-1}$ . This water may then evaporate like free water.

#### 3.5.2. Soil surface status

The state of the soil surface can modify the water and heat balances of the soil–crop system. The soil surface is characterised by its albedo when dry, a surface run-off coefficient giving the pro-

Table 2

Simulation of the effect of various types of soil covering beneath the crop on the main agro-environmental outputs for a sugar cane system in Guadeloupe on a Vertisol (1330 mm rainfall during the season; parameterisation based on the work of Ozier-Lafontaine (1992))

	None	0.5 Mg ha <sup>-1</sup> maize mulch	5 Mg ha <sup>-1</sup> maize mulch	Black plastic mulch
Yield (Mg ha <sup>-1</sup> )	25	35.5	40	31
Plant transpiration (mm)	540	839	967	800
Soil evaporation (mm)	382	317	171	99
Mulch evaporation (mm)	0	14	135	0
Drainage (mm)	98	120	212	108
Surface run-off (mm)	492	217	25	492
Mineralisation (kgN ha <sup>-1</sup> )	139	171	182	172

portion of run-off water above a starting threshold, and the presence of plant or plastic mulch.

The processes modelled are:

- the estimation of plant mulch dynamics and of the corresponding proportion of soil covered (Scopel et al., 1998)
- the modification of surface run-off affected by the presence of obstacles at the soil surface (Scopel et al., 1998)
- water interception by plant mulch and the direct evaporation of this water
- the reduction in soil evaporation caused by the presence of mulch
- the effects of such a modification in the flows on the climatic requirements of the plant
- the modifications in crop temperature related to the modification in the flows and soil surface albedo.

The importance of these mechanisms is illustrated in Table 2 for sugar cane simulations in Guadeloupe.

### 3.5.3. Fertilisers

Mineral nitrogen originates from fertilisers, irrigation water and rainwater (concentration estimated to be  $0.02 \text{ kgN ha}^{-1} \text{ mm}^{-1}$ ). Fertiliser losses through volatilisation and immobilisation are parameterised according to the type of fertiliser.

As regards the organic supplies, decomposition parameters are calculated for several organic residue categories (main crop residues (mature plants), intermediate crop residues (young plants), manure, compost, sludge, ...) as a function of the C/N ratio of the residue (Hdadi, 2000). The residues are distributed in the soil profile depending on the soil tillage operations.

Part of the nitrogen in organic fertilisers containing ammoniacal nitrogen volatilises. The environmental importance of this mechanism led us to propose a method for calculating volatilisation dynamics. In soil, ammoniacal nitrogen exists in ionic ( $\text{NH}_4^+$  either adsorbed on soil mineral or organic fractions or in solution in the soil liquid phase) and molecular ( $\text{NH}_3$  either in the soil liquid phase or in the soil atmosphere) forms in equi-

librium with each other, one of which is in gaseous form. All that which modifies this equilibrium towards the gaseous form (high pH and temperature) promotes volatilisation, which occurs at the soil surface. It depends on the mineralogical composition of the soil, its organic matter content, its pH and its temperature. The equations incorporated into STICS correspond to the model of Générmont and Cellier (1997) applied on a daily time-scale. The volatile fraction of the organic fertiliser depends on its water content and on the structural state of the soil according to a relationship proposed by Morvan (1999).

### 3.6. Microclimate

The daily crop temperature is assumed to be the

Net radiation is written as:  $r_{net} = (1 - \text{albedo})r_g + r_{atm} - r_{sol}$ ,  $r_g$  being the incident global radiation. Atmospheric radiation,  $r_{atm}$ , is calculated from the [Brutsaert \(1982\)](#) formula, which uses temperature and air humidity as input variables. If the air humidity variable is unavailable, it is estimated by hypothesising that the minimal air temperature coincides with the dew-point temperature. Albedo varies between the soil value and the vegetation value according to the formula of [Ritchie \(1985\)](#). Soil albedo varies according to the type of soil, the moisture in the surface layer and, possibly, the presence of a plastic or plant cover. Soil radiation,  $r_{sol}$ , is a function of crop temperature (a variable that is to be calculated) and is therefore the object of an iterative calculation based on a convergence criterion of 0.5 °C.

The simplified approach to calculating the crop temperature is based on a relationship between surface temperature in the middle of the day and daily evaporation ([Seguin and Itier, 1983](#); [Riou et al., 1988](#)). In this approach, it is hypothesised that the minimal crop temperature coincides with that of the air.

The energy balance approach is based on two calculations made at the time of the maximum and minimum temperature. Atmospheric radiation is assumed to be constant throughout the day, whereas soil radiation is calculated with the maximal and minimal temperatures (same iterative processes as above). At the end of the night, the flow of heat in the soil is calculated as an empirical function of wind under the canopy and of minimal net radiation ([Cellier et al., 1993](#)). The flow of heat in soil at midday is taken to be equal to 25% of maximal net radiation under the canopy. Total radiation and evaporation in the midday sun are estimated assuming that the flows evolve sinusoidally during the day. Night-time wind is assumed to be equal to  $0.5 \times$  daily mean wind and daytime wind is assumed to be equal to  $1.5 \times$  daily mean wind. These wind values were used to calculate aerodynamic resistance ([Brisson et al., 1998c](#)).

The comparison between the simplified relationship and the energy balance ([Fig. 8](#)) shows that the energy balance calculations give slightly higher temperature estimations than the simplified rela-

tionship, particularly in the case of high temperatures over bare soil.

Once the sum of evaporative fluxes is known ([Section 3.7](#)), the saturation deficit within the canopy is estimated using the formula of [Shuttleworth and Wallace \(1985\)](#). The humidity is thereafter deduced from the saturation deficit using crop temperature. In the case of limited climatic data (no wind, no air humidity), the aerodynamic resistance of the atmosphere above the canopy takes on a default value ( $50 \text{ s m}^{-1}$ ).

### 3.7. Water balance

The water balance is used to calculate the water status of the soil and the plant as well as the water stress indices that reduce leaf growth and net photosynthesis. It is based on estimating the water requirements of the soil–leaf system on the one hand and on the water supply to the soil–root system on the other.

#### 3.7.1. Soil evaporation

Soil evaporation is calculated in two steps: potential evaporation related to the energy available at the soil level and then actual evaporation related to water availability. It is then distributed over the soil profile.

There are two methods for calculating potential evaporation, related to plant cover above the soil (using either LAI or soil cover fraction) and the possible presence of an inert cover placed on the soil ([Brisson et al., 1998c](#)). The first corresponds to a Beer law equivalent applied to the potential evaporation/reference evapotranspiration ratio (Penman) with a constant extinction coefficient. The second is an energy balance approach.

The calculation of actual evaporation, described in detail in [Brisson and Perrier \(1991\)](#), is based on concepts that resemble those put forward by [Ritchie \(1972\)](#).

The calculation of the distribution of evaporation in the soil profile, is based on the exponential decline of the contribution of each 1 cm soil layer, until a depth that is taken equal to 60 cm, which is similar to the LIXIM model ([Mary et al., 1999](#)).

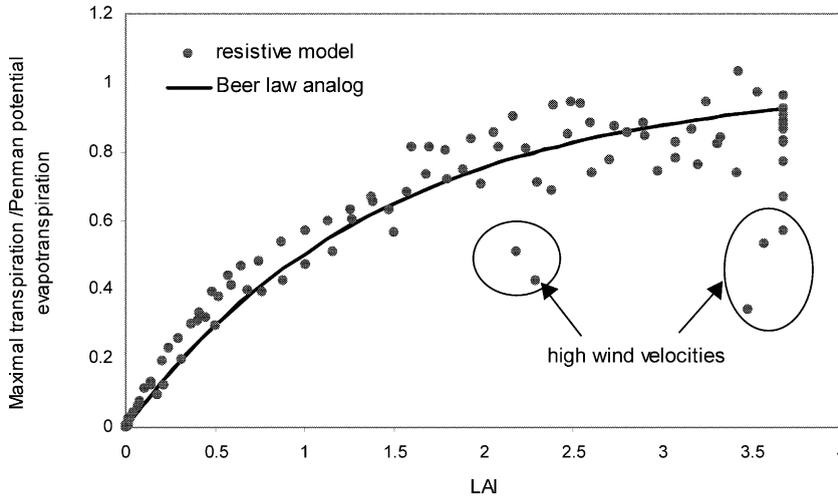


Fig. 9. Comparison of the two methods for calculating plant water requirements (Beer law analog and resistive model) for an irrigated maize crop.

3.7.2. Crop water requirement

As part of the Beer law approach (described in [Brisson et al., 1992b](#)), the potential evaporation of the crop is calculated assuming that none of the soil surfaces or plant surfaces are water-limited. This evaporation is a logistic function of LAI or soil cover fraction, involving a maximal crop coefficient reached for a LAI of about 5 or a soil cover fraction of about 1. If water has been intercepted by the foliage or by plant mulch placed at the soil surface, this water is evaporated depending on the reference climatic demand and continues to reduce the climatic demand exerted on the crop.

Maximal transpiration depends on the energy available for the plants, estimated from the

difference between the crop potential evaporation and the soil potential evaporation, but also on the state of the atmosphere in the vegetation using the actual/potential soil evaporation ratio.

The energy balance (or resistive) approach is based on an adaptation of the model of [Shuttleworth and Wallace \(1985\)](#) at a daily time-step, described in [Brisson et al. \(1998c\)](#). It is used when

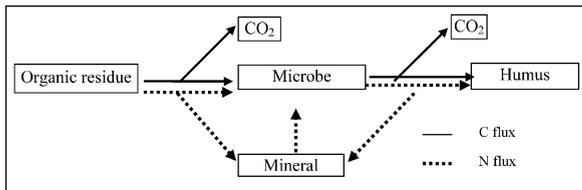


Fig. 10. Diagram of the model describing the C and N fluxes occurring during the decomposition of organic residues in soil by the (zymogenous) microbial biomass (see details in [Nicotardot et al., 2000](#)).

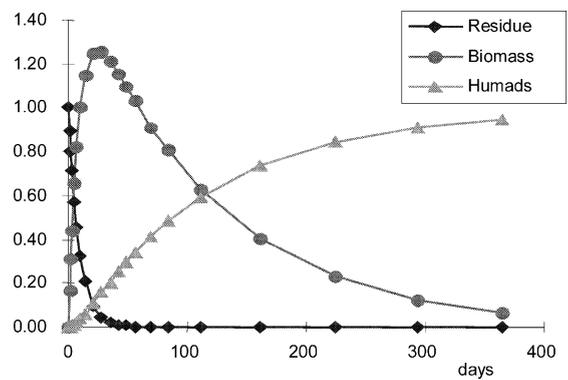


Fig. 11. Simulated evolution of nitrogen in crop residue, microbial biomass and newly formed humus during the decomposition of rapeseed residues (C:N = 45) in soil at constant temperature (15 °C) and moisture (85% WHC). The nitrogen is expressed as a fraction of nitrogen added by the rapeseed residues. Values greater than 1 indicate that soil mineral N was immobilised by the microbial biomass.

Beer's law cannot be applied simply (crops in rows) and it is more reliable with respect to the 'soil evaporation' variable and to the effect of the microclimate surrounding the plant. For example in the case of high wind velocities, the contribution of soil evaporation is increased in relation to that of the plant, which cannot be reproduced using Beer's law with a constant extinction coefficient (Fig. 9). The resistive method requires data concerning wind and air humidity and is based on two parameters: minimal resistance of the leaves and maximal height of the canopy. Canopy resistance takes the LAI, radiation and air saturation deficit into consideration as well as its CO<sub>2</sub> content (simulation of the impact of climatic change). Canopy height dynamics, which are important for estimating roughness, is calculated from the maximal height and LAI.

The former process is perm 350.rpi7.cleafsimu4364 i.e.procc

### 3.7.3. *Transpiration*

Root absorption and leaf transpiration are assumed to be identical; total root absorption is calculated and then distributed over the soil layers according to the effective root density profile.

Relative transpiration, i.e. the ratio of actual transpiration to potential transpiration, is a bi-linear function of the available water content in the root zone. The water content threshold, discriminating the maximal transpiration phase from the reduced transpiration phase, depends both on the root profile, the stomatal function of the plant (critical potential for stomatal closure) and climatic requirements (described in detail in [Brisson, 1998](#)).

Relative transpiration is equal to the stomatal stress index and affects RUE. The stress index affecting leaf growth intervenes earlier; it is calculated in the same way as the stomatal index using the critical potential for cell expansion, which is lower than the critical potential for stomatal closure.

## 3.8. *Nitrogen balance*

### 3.8.1. *Mineralisation*

Net nitrogen mineralisation in the soil is the sum of humus mineralisation and the mineralisation of organic residues (crop residues or organic wastes).

partitioning coefficient accounts for the effects of pH, temperature and water content on nitrification, which are assumed not to interact with each other (Sierra and Marbán, 2000; Sierra et al., 2001). Of course temperature and water content effects on nitrification are different from the effects of the same physical variables on ammonification. This approach is equivalent to assuming an average lifetime of ammonium. Only the nitrate concentration is considered in the leaching calculations. Conversely, nitrogen uptake by the plants is calculated on the basis of the total amount of mineral nitrogen in the soil (no selectivity for  $\text{NO}_3^-$  and  $\text{NH}_4^+$ ). In the case of fertilisation, it is necessary to give the proportion of ammonium in the fertiliser.

### 3.8.2. Denitrification

The gaseous losses by denitrification (sum of  $\text{N}_2$  and  $\text{N}_2\text{O}$ ) are estimated by the NEMIS model (Hénault and Germon, 2000). The denitrification processes are calculated for each 1 cm layer in the sub-surface horizon, as the product of a denitrification potential by a variable representing the favourableness of the conditions for denitrification. This variable is the product of three effects for soil temperature, anoxia and nitrate.

### 3.8.3. Nitrogen absorption

The daily absorption of nitrogen is equal to the minimum of supply available through the soil–root system and crop requirements.

Crop requirements correspond to a relationship established from the upper envelop of nitrogen dilution curves (Lemaire and Gastal, 1997).

Soil nitrogen supply is calculated per 1 cm layer along the rooting depth. It is equal to the minimum of the following two fluxes:

- the transport flux: nitrate transport from a point in the soil towards the closest root, via convection (simulated according to the transpiration flow) and diffusion (use of an apparent nitrate diffusion coefficient).
- the sink flux: active absorption by the root, an active physiological process in the plant that depends on its intrinsic capacity to absorb, the root density and the nitrate concentration in the

surrounding environment. Specific absorption (per root length unit) increases with nitrate concentration according to two Michaelis–Menten kinetic equations corresponding to two transport systems: one high affinity system and one low affinity system.

The plant nitrogen content/critical content (calculated with the critical dilution curve) ratio corresponds to the nitrogen nutrition index (INN), from which the nitrogen stress indices are derived.

In the case of legumes, symbiotic fixation can be simulated with two options. A first simple option assumes that symbiotic fixation maintains nitrogen nutrition at the critical nitrogen level. Additional nitrogen absorption from the soil solution is added to this fixed nitrogen. The result is that plant nitrogen content is always between the critical and the maximum levels. This option does not make it possible to account for limitations in nitrogen nutrition, incorporate genetic variability or correctly estimate nitrogen residues. A more sophisticated option, available in version 5.0, relies on the dynamics of the potential activity of nodules and accounts for the limiting factors of symbiotic fixation such as the presence of nitrates, water stress, anoxia and temperature (Burger, 2001; Debaeke et al., 2001).

## 3.9. Transfers in the soil

### 3.9.1. Soil temperature

The dynamics of temperatures in the soil depend on the surface conditions driving the daily thermal wave and on heat inertia of the soil that is responsible for reducing the thermal wave in deeper layers. Daily crop temperature and its amplitude are used as upper limits for the calculations of soil temperatures. The amplitude in depth and then the soil temperatures are calculated using the model of McCann et al. (1991). Thermal diffusivity is constant; the value of  $5.37 \cdot 10^{-3} \text{ cm}^2 \text{ s}^{-1}$  is an average for numerous soils under various water conditions (Buchan, 1991).

### 3.9.2. Transport of water and nitrogen in soil

The description of soil includes four compartments: microporosity (or textural porosity), macroporosity (or structural porosity), fissures (in the case of swelling clay soils) and stones. The soil is divided in 5 horizons but calculations in the microporosity are done per 1 cm layer, which is the resolution required to derive nitrate concentration.

Water transport in soil micropores is calculated for each 1 cm layer using a tipping bucket approach. Water supplies cascade down filling up the layers until field capacity. The permanent features of the 1 cm layers (field capacity, permanent wilting point and bulk density), as well as the initial water contents, are deduced from those of the 5 horizons describing the soil. At the surface, the soil can dry out until residual humidity is reached in relation to soil evaporation. Deep in profile, this is more rare because water absorption by plants is limited by the permanent wilting point.

In version 4.0 the nitrogen concentration of the soil solution was calculated for each 1 cm layer, imposing, by default, a dispersivity value of 0.5 cm (Mary et al., 1999). In version 5.0, this dispersivity can be parameterised per soil type, which allows a more realistic simulation of nitrate leaching (Justes et al., 2001). For each layer, the nitrogen concentration of the soil solution is calculated. There may be a lower concentration threshold below which nitrogen is prevented from leaching. Above this threshold, the soil water and nitrogen is assumed to be perfectly mixed and the nitrogen leached.

When stones are present, the permanent features of the horizons are modified according to the amount and type of stones. The type of stone is characterised by a bulk density and a water holding capacity.

The macroporosity and the fissure compartments play a role in drainage and run-off processes. The macroporosity functioning is simulated at the level of the horizon (not per cm) whereas the fissures are supposed to be independent of the layer/horizon soil partitioning.

For each horizon, a daily infiltrability parameter is defined that can limit the amount of infiltrated water thereby filling up the macropores in the horizon. For non-swelling soils, macropor-

osity is calculated as usual on the basis of total porosity (a function of bulk density) and field capacity. For swelling clay soils (potential existence of fissures), macroporosity is estimated from half the difference between field capacity and the permanent wilting point.

If the macropores in the horizon are filled, the anoxia index of each horizon layer is given the value of 1 and the water begins moving upwards. The water thereby reaching the horizon above can be used to resupply the micropores (where water is taken up by the plant), before filling the macropores.

When fissures are open, they are filled up by overflow of the surface horizon; water supply via the interception of rainfall at the surface is disregarded. The opening of fissures depends on the combination of two factors in at least one of the horizons: empty macropores and a root front below the horizon base.

### 3.9.3. Agricultural drainage

It was necessary to adapt the models usually used for drainage to incorporate the agricultural drainage into version 5.0 of STICS. Two difficulties needed to be overcome: (1) the required time-step for simulating functioning of a draining system in a temperate climate is much closer to 1 h than to 1 day; (2) the functioning of a draining system is 3D and not 1D.

The standard draining system uses the properties of symmetry due to the presence of drain lines in a field with a constant distance between drains. The flow is supposed to occur from the middle of the field between two parallel drains to the drain; this flow occurs within a water table located on an impermeable level of variable depth (this depth may be higher than the soil depth considered in STICS).

The equation of Hooghoudt, used to simulate draining systems, is usually available for a permanent regime but we have shown (Zimmer, 2001) that, for a sufficiently long time-step, the same equation provides correct predictions of flows and water table heights.

## 4. Data requirements

### 4.1. Minimum data to run the model

The choice of when to begin the simulation process is important for initiating the system. If it is before sowing (annual plants) or at vegetative rest (perennial plants), the initiation only concerns the soil; if it is during vegetation (at precise development stages), it also concerns the state of the plant.

#### 4.1.1. Climate

Daily climatic variables are required: minimum and maximum temperatures, radiation and rainfall. Three options are available for calculating the evaporative demand of the atmosphere; the first two imply the use of the “Beer’s law” model for calculating the water balance and the last one corresponds to the use of the energy balance:

- calculation of a reference evapotranspiration value according to the formula of [Priestley and Taylor \(1972\)](#), and the coefficient can be modified in order to adjust the formula to the study site. This option is advantageous in that it requires no additional climatic variables.
- forcing of reference evapotranspiration as an additional climatic variable.
- the energy balance which makes it possible to directly estimate water requirements at the plant and soil levels without the necessity of a climatic reference but rather two additional climatic variables: daily mean wind (at a height of 2 m) and daily vapour pressure.

#### 4.1.2. Soil

The input properties for the surface horizon of soil (depth of which is an input parameter) are the following: organic nitrogen content, active lime content, clay content, albedo when dry, run-off coefficient, pH, soil evaporation accumulation during the potential phase. Other properties for the full soil profile are: mineral nitrogen concentration protected from leaching, depth of a physical or chemical obstacle to rooting. Lastly, the parameters concerning soil hydrodynamic functioning are provided for each horizon: field

capacity, permanent wilting point, bulk density, stone content and type of stone, infiltrability.

Most of these parameters are obtained from standard chemical or physical analyses. A few parameters require specific measurements. Nevertheless, the orders of magnitude found in the literature can be used as a basis for an initial parameterisation for example for albedo, potential soil evaporation threshold or infiltrability ([Richard and Cellier, 1998](#); [Jacquemoud and Baret, 1992](#); [Ritchie, 1972](#); [Brisson and Perrier, 1991](#)). It is also possible to obtain some of the parameters that are difficult to access by optimising the dynamics of the state variables such as water content or surface temperature.

The initialisation of soil profiles requires inputs for water, mineral nitrogen and, possibly, root density in the case of perennial plants.

#### 4.1.3. Management

Most of the crop management has been incorporated into the model: sowing (date, depth, density, variety) or planting (interrow, row orientation), mineral and organic fertilisation, irrigation, fertigation, soil tillage with ploughing-in of residues, use of plant or plastic mulching, thinning, cutting (forage) or harvesting (once or several times) using various criteria (physiological maturity, water, nitrogen, sugar or lipid contents).

With respect to mineral fertilisation and organic residues, correspondence tables were incorporated that make it possible to associate a fertiliser or residue with the appropriate nitrogen dynamics parameters.

#### 4.1.4. Genetic parameters

Several plant specific parameters are assumed to depend on the variety ([Brisson et al., 1998a](#)), i.e. (1) the duration of the phenological phases and cold requirements (vernalisation or dormancy) if applicable; (2) three parameters that affect leaf growth, root growth and the final size of harvested organs. In order to obtain parameters for new varieties, it is important to know the developmental phases on which genetic variability is based ([Brisson et al., 2002](#)) and to have access to at least two sets of data obtained in contrasting environments in order to adjust the growth parameters.

## 4.2. Validation of the model

### 4.2.1. Data required to validate the model

The validation consists of comparing the observations with the results of the simulations, for key agronomic and environmental variables, i.e. key phenological stages, yield and its components, aboveground biomass, amount of nitrogen in the plant and in the harvested organs and variations in the amounts of water and mineral nitrogen in the soil during the cultivation and fallow periods. This list of validation variables applies to most crop models.

### 4.2.2. Forcing

By forcing certain state variables it is possible to partially validate the model. In the case of STICS, it is possible to force the developmental stages independently of each other and to use the measured LAI. In the case of the LAI, measured values are interpolated on the basis of a growth (logistic)-and-senescence (exponential) function according to the sum of degree-days from the beginning of the cycle ([Ripoche et al., 2001](#)).

### 4.2.3. Observed data and optimisation

The observed values of the main state variables make it possible to graphically assess the quality of the model, calculate the statistical criteria for validating the model (root mean square errors, efficiency, mean deviation, etc) and calculate the parameter values by optimisation. The optimisation module, that was specifically developed for STICS, is based on a simplex algorithm and uses a root mean square error as a convergence criterion. It is possible to optimise up to 5 parameters at the same time, for various state variables (LAI, biomass, mass and number of harvested organs, root front, soil water content, amount of mineral nitrogen in the soil and in the plant, leaching, drainage, crop temperature). These tools are sometimes limited but other validation criteria and other optimisation methods exist ([Mazzetto and Bonera, 2001](#); [Acutis and Donatelli, 2001](#)).

## 5. Software implementation and distribution policy

The STICS model is written in FORTRAN 77 and operates on a standard PC-compatible microcomputer in a user-friendly Windows env

grammes Protection Agency). The licence stipulates among other things that the software is an educational product designed exclusively to be used for educational purposes, and that it is forbidden to reproduce, translate, adapt, arrange or modify either the software or the documentation that comes with it for commercial purposes. It is available to all users in the form of a CD-ROM including the instructions, and its cost covers only the CD-ROM medium and postage (about 30€).

## 6. Model testing and applications

### 6.1. Model validation

Although STICS includes ‘plant’ parameterisation for many species (wheat, barley, maize, soybean, sorghum, rapeseed, flax, tomato, sunflower, beetroot, potato, forage grasses, lucerne, lettuce, carrot, banana, sugar cane, mustard), the validation status of the model varies greatly from one species to another. For example, in the case of wheat and maize, the two ‘oldest’ STICS crops, the model reliability has been assessed on the basis of a great number of field conditions (Brisson et al., 2002). For other crops, the plant parameterisation and validation are based on a more limited number of field conditions. A synthesis of some experiments used to validate STICS for various species is presented in Fig. 12. A sensitivity analysis to the model parameters was carried out for each module (Ruguet et al., 2002), which makes it easier to choose the methods (literature, optimisation of state variables related to the parameter, direct measurement) to be used to give values to the parameters (Ghiloufi, 1999).

### 6.2. Examples of application

In an agricultural context where inputs are limited (for reasons concerning the environment, product quality, etc.), it is difficult to explain the interaction between mechanisms without the help of a model. STICS thereby appears, like many other crop models, to be useful for research on cropping systems and for assessing their agronomic or environmental impacts. The model makes it pos-

sible to transfer knowledge to related disciplines (hydrology, climate modelling, economy, etc..) by using simple model formalisations or analogies, allowing them to simulate the part of the system that they do not know. The heuristic potential of the model can also be interesting. In fact, as a result of its shortcomings, the model reveals the areas that need to be clarified and new areas that need to be explored.

Two studies can exemplify the heuristic role of the model. First, when analysing the effect of water deficit on wheat grown in Argentina using the model, the results indicated that water deficiency first acted on nitrogen availability for root uptake inducing a nitrogen stress before the water stress appeared (Brisson et al., 1997), which was confirmed by further experiments. Second, the simulated default of the water balance of a banana crop in West Indies helped us understanding the role of the amount of rain intercepted by the foliage in such tropical conditions (Brisson et al., 1998b).

Until now, the STICS model has been used at the agricultural plot scale to make agronomic or environmental diagnoses (e.g. influence of soil tillage and irrigation on the cultivation of the banana, Brisson et al., 1998b) or to evaluate crop management schedules (irrigation timing for a maize crop, Levrault and Ruguet, 2002; optimisation of intermediate crop management, Justes et al., 2001). It is also being used at the intra-plot scale in a precision farming framework (Bruckler et al., 2000). However, at this intra-plot scale, one could question whether the model is sufficiently sensitive to its input variables to reproduce the spatial variability studied.

At the regional scale, STICS has been used to estimate the potential of an environment (e.g. classification of soils in a region according to their mineralisation potential) or to make agronomic diagnoses on a large scale using remote sensing (assimilation of remotely sensed data into the STICS model coupled with a model of the radiation response of plant canopies: Weiss et al., 2001). It has also been used in association with a hydrological model to estimate nitrate leaching at the scale of a watershed or a region (Beaujouan et al., 2001). As part of the ISOP (Prairies Information

and Objectives Survey: Ruget et al., 2002) programme, STICS gives estimations of forage production in real time for the whole French territory. Some studies used the STICS model to test the effects of climatic changes on wheat yield (Bellia, 1999), on the flowering of fruit trees (Domergue, 2001) and on forage cuttings in mountainous areas (Juin, 2001). It can also contribute to socio-economic studies (Affholder, 2001).

### 6.3. Limitations of the model

The type of mechanisms simulated partly defines the model's validity range; certain environment  $\times$  management combinations are therefore excluded from its range of applications. For example, since the model does not simulate phosphorus or potassium dynamics in the soil–plant system, any reduction in yield related to the plant being deficient in these elements, as well as the management aimed at rectifying these deficiencies, are beyond the validity range.

Although the number of main output variables is limited, the number of subsidiary variables is much higher and consequently it is useful to consider validation for these subsidiary variables. However, given the simplicity of the model formalisations and the irregular sensitivity of these variables this would not make much practical sense. For instance, LAI could be over-estimated for values of over 3 or under-estimated during a period of low radiation, but this would have little effect on the related functional output variables such as biomass production and water transpiration. Nevertheless, these subsidiary variables must not be ignored because they make it possible to make a diagnosis on the model's performance.

Also, there is a difference between the scales expected for the results of the model and the scales required for describing the processes. For example, the coupled water and nitrogen balances in the soil are solved at the scale of 1 cm, but soil characterisation and thereafter the assessment of water and nitrogen profiles are based on dividing the soil into a maximum of 5 horizons.

The model is still a simplification of reality that is justified by the reasons for which it is to be used and that must be respected. In the scientific fields

where biology has an important role, models must not be considered to be 'simulators' of reality such as in the field of physics, but simply as tools for interpreting a highly complex reality.

## 7. The link between development and application

All the users of the STICS model form a group that participates in making the model and the software evolve. Communication between the users and the modellers is undertaken periodically. As a result of these discussions, the idea emerged that STICS should not be made a fixed model but rather an interactive modelling platform. It is possible to distinguish between two user populations that are not necessarily disconnected: the modellers, who are interested in the model formalisations, and the users, in the strict sense of the word, who are interested in the output variables. The former group is tempted to suggest improvements or complements to STICS in order to be able to take a particular mechanism into consideration, incorporate a specific species, or simply improve what already exists. The latter group wants to use the model (all or some of it) without questioning how it functions; they may be guided to modify certain parameters related to a particular environment or to suggest improvements concerning the user-friendliness of the model. In order to enable one and all to contribute effectively to STICS, the model has to be easy to specify and accessible both in terms of parameterisation and programming. After each meeting, a 'current' version is set as a result of the proposals made by the various participants and adopted by consensus.

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